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Interacting compact binaries: modeling mass transfer in eccentric systems

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Abstract. We discuss mass transfer in eccentric binaries containing a white dwarf and a neutron star (WD–NS binaries). We show that such binaries are produced from field binaries following a series of mass transfer episodes that allow the white dwarf to form before the neutron star. We predict the orbital properties of binaries similar to the observed WD–NS binary J1141+6545, and show that they will undergo episodic mass transfer from the white dwarf to the neutron star. Furthermore, we describe oil-on-water, a two-phase SPH formalism that we have developed in order to model mass transfer in such binaries.

1 Introduction

Interacting compact binaries are responsible for a wide range of astronomically interacting events. Accreting white dwarfs (WDs) are believed to be the progenitors of type IA supernovae. Cataclysmic variables also occur when white dwarfs accrete matter but under different conditions. Higher-mass accretors – neutron stars (NSs) or black holes (BHs) form X-ray binaries. A recent paper (Metzger 2011) suggests that the tidal disruption of a WD by either a NS or a BH may lead to an accretion flow that is dominated by nuclear burning, with a potentially unique nucleosynthetic signature.

Here we consider the problem of modeling the onset of mass transfer in an eccentric binary containing a white dwarf and a neutron star, a potential progenitor of such a nuclear-dominated accretion flow. We discuss the formation of such binaries and show that when they come into contact they are expected to undergo episodic mass transfer. Finally we outline the oil-on-water SPH technique that we have developed to study these binaries.

2 Formation of eccentric WD–NS binaries

There are two clear detections of eccentric binaries containing a white dwarf and a neutron star; B2303+46 (van Kerkwijk & Kulkarni 1999) and J1141-6545 (Kaspi et al. 2000). One might expect that such binaries would not exist, as the neutron star, having a more massive and hence rapidly evolving progeni-

tor, should form first. Tidal circularisation during the giant phase of the white dwarf's progenitor would then remove any eccentricity imparted by the supernova. Therefore, to produce such a binary, the white dwarf must form first.

A formation mechanism was outlined by Portegies Zwart & Yungelson (1999) and developed by Tauris & Sennels (2000), Davies et al. (2002) and Church et al. (2006). In it, the binary initially contains two main-sequence stars of similar, but not identical, mass, and has an orbital separation of around $100 R_{\odot}$. The initially most massive star fills its Roche Lobe in the Hertzsprung gap and transfers mass stably to its companion. Subsequent phases of mass transfer can follow several pathways, but in all cases the initially most massive star fills its Roche lobe again, transfers the majority of its mass to its companion and finally becomes a white dwarf. The companion star is now massive enough to evolve a Chandrasekhar-mass degenerate core, which collapses leading to a supernova and, if the resulting binary is bound, the formation of an eccentric binary. We refer to such systems as WD–NS binaries.

Church et al. (2006) predict the binaries similar to J1141-6545 form when a fourth episode of mass transfer occurs after the white dwarf has formed. This mass transfer is inevitably from the most massive star at this point (the progenitor of the neutron star) and hence causes the orbit to shrink, producing a tighter binary after the supernova. Such close binaries merge in less than the Hubble time and hence are of interest to us.

Following the formation of the binary, the emission of gravitational waves causes its orbit to shrink and circularise (Peters 1964). In the fully circularised case, mass transfer from the white dwarf begins once it fills its Roche lobe. However, these binaries still have a residual eccentricity at this point. In Figure 1 we plot the orbital properties for a sample of WD–NS binaries that form via a pathway similar to that inferred for J1141-6545, as computed by BSE (Hurley et al. 2002). It can be seen that our simulations produce binaries with orbits similar to that of J1141-6545. The residual eccentricity when these binaries come into contact is typically between 10^{-2} and 10^{-4} . As the surface pressure scale height of white dwarfs is very small these eccentricities are large enough for episodic mass transfer to occur.

3 Using smoothed-particle hydrodynamics in eccentric binaries

In order to model episodic mass transfer in eccentric WD–NS binaries we have developed an extension to SPH which we call oil-on-water. SPH is a Lagrangian particle-based method for solving the equations of hydrodynamics (Lucy 1977; Gingold & Monaghan 1977). The implementation that we use follows Benz (1990). In vanilla SPH, one requires a very high mass resolution to model mass transfer between stars. For example, in a cataclysmic variable the mass transfer rate is 10^{-9} to $10^{-8} M_{\odot} \text{ yr}^{-1}$ (Patterson 1984); given a typical orbital period of 1 day the mass transferred per orbit is one part in 10^{12} of the total mass. For studies of continuous mass transfer in circular binaries this is not a problem, as the flow is steady and hence can be considered over a large number of orbits. In the case of episodic mass transfer that switches on and off each orbit, however, a new approach is required.

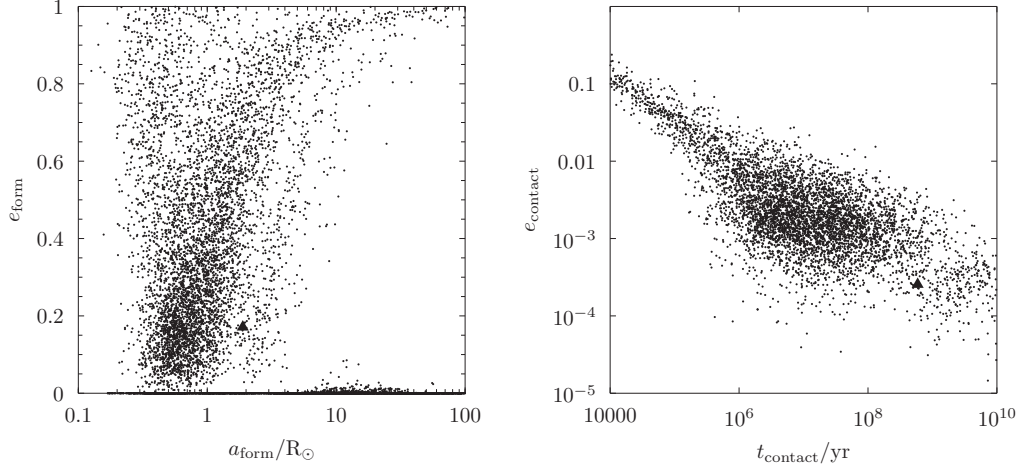


Figure 1. Left panel: The eccentricities of our simulated sample of WD–NS binaries as a function of their semi-major axis, both at formation time, i.e. just after the supernova. The filled triangle represents J1141+6545. Right panel: Eccentricities of WD–NS binaries at the point when the white dwarf fills its Roche lobe, as a function of the time taken for them to spiral together.

To avoid this problem we split the star up into two separate phases. Heavy “water” particles form the body of the star and account for essentially all of its mass. Light “oil” particles form an atmosphere that is transferred during interactions between stars. As the mass of the oil particles is much less than that of the water particles numerical stability requires them not to come into contact. To prevent this from happening we introduce an additional force to stop the oil particles sinking into the star. This additional force, acting on an oil particle of mass m_i , depends on the water particle number gradient n as

$$F_n = \beta \frac{GM_\odot m_i}{R_\odot} \nabla n; \quad \nabla n = \sum_j \nabla W^{\text{ow}}(r_{ij}, h_{ij}) \quad (1)$$

where β is an adjustable parameter. We utilise a different kernel W^{ow} with a break point at a smaller multiple of the smoothing length h in order to keep the oil layer closer to the surface of the star. Full details of the method are given in Church et al. (2009). It should be noted that the oil particles are *not* test particles; they obey the full SPH equations when interacting with one another, which lets us follow the processes inside the accretor’s Roche lobe.

To test the validity of the model we investigated mass transfer from a low-mass star to a white dwarf in eccentric binaries. For the body of the star we used 15 390 water particles with a total mass of $0.6 M_\odot$. The atmosphere was made up of 39 691 oil particles with a mass of $10^{-14} M_\odot$ each. This stellar model was placed into a binary with a $1 M_\odot$ white dwarf, modelled as a point mass, and relaxed at apocentre. The orbit was then made eccentric. For each eccentricity we varied the semi-major axis in order to find the pericentre separation at which mass transfer started. We found that mass was transferred on each orbit shortly after pericentre passage, and that the semi-major axis required for mass transfer decreased with increasing eccentricity, compared with the value that would be

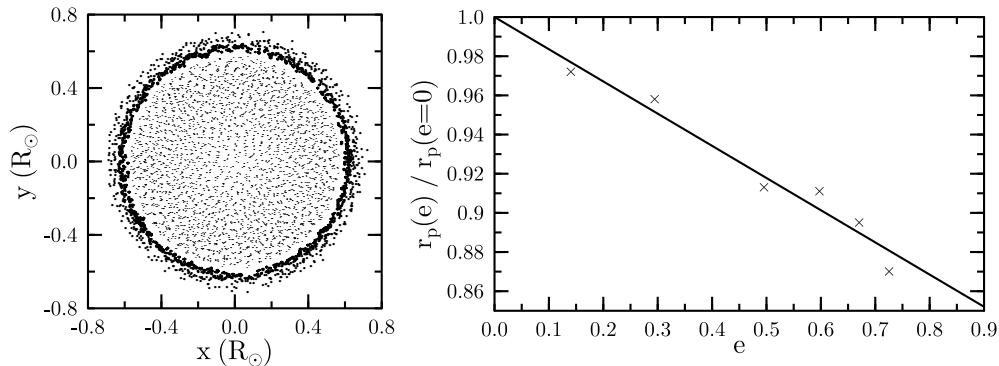


Figure 2. Left panel: structure of an oil-on-water star. Particles within h of the $x - y$ plane only are plotted. The oil particles are plotted with larger dots. A clear atmosphere can be seen within the oil layer. Right panel: the ratio between the periastron separation required for mass transfer assuming that the star must fill its Roche lobe at periastron and that measured from our simulations, plotted as a function of eccentricity. The minimum separation required for mass transfer to take place is seen to decrease linearly with increasing eccentricity.

implied by requiring the star to fill its Roche lobe at pericentre (see Figure 2). This is in agreement with the results of Sepinsky et al. (2007), who take an analytical approach to determining the point of onset of mass transfer.

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